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WEATHER BUREAU
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MONTHLY WEATHER REVIEW

JAMES E. CASKEY, JR., Editor

Volume 84
Number 12

DECEMBER 1956

Closed February 15, 1957
Issued March 15, 1957

CLOUD SYSTEMS AND PRECIPITATION PROCESSES IN PACIFIC COAST STORMS

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[Manuscript received September 18, 1956; revised November 28, 1956]

ABSTRACT

From the records obtained during the Weather Bureau Artificial Cloud Nucleation Project carried out in western Washington State during the winters of 1952–53 and 1953–54, it is possible to study the nature of some of the precipitation processes evident in that locality, and to form a preliminary generalized picture of certain types of cloud systems involved. Evidence is presented of natural seeding mechanisms and of the growth of hydrometeors by diffusion, coalescence, aggregation, and accretion. Typical wintertime cloud systems, and the attendant precipitation processes are illustrated.

1. INTRODUCTION

The systematic investigation from aircraft of the physical processes involved in the production of precipitation is relatively rare. The many flights into winter storms in western Washington State by the cloud seeding aircraft of the Weather Bureau Artificial Cloud Nucleation (ACN) Project during the winters of 1952–53 and 1953–54 provided an excellent opportunity for the observation and study of precipitation processes and the cloud systems related to them. During a typical operation, one of the airplanes would orbit over a relatively small geographical area for several hours while the storm elements moved past it. During such periods, the flight meteorologist on board kept a detailed log of the cloud conditions and, when feasible, took photographs of the changing meteorological situation. In addition, cloud particle samples were taken, and air temperature, air speed, pressure altitude, and icing rate were automatically recorded.

From these records, it has been possible to derive evidence, either by direct observation or by inference, concerning the nature of some of the precipitation processes encountered, and to form a generalized picture of certain types of cloud systems involved. The emphasis here is on the interaction *between liquid and solid particles in the clouds* which result in precipitation at the ground; thus, formation of the clouds necessary for precipitation is not considered. Rather, this discussion concerns the fairly well known basic precipitation processes, such as natural seeding, diffusion, coalescence, aggregation, and accretion, as they apply to the inflight observations, and emphasizes some of the precipitation complexes that seemed to be typical of the temperate latitude storm systems that occurred in western Washington during the course of the test program.

Due to the great amount of time necessary for assembling and evaluating the many flight records and cloud sampling slides accumulated during the project operations, the inclusion of more than a sampling of the available quantitative data has not been possible. Hence this paper is necessarily of a preliminary nature and the conclusions are to a degree inferential.

2. PRECIPITATING CLOUD SYSTEMS

One of the more common precipitation complexes, observed to occur in the eastern portion of storms, involved a situation of multi-layered clouds, where ice crystals were generated in an upper layer consisting primarily of liquid cloud, and were falling through one or more lower-

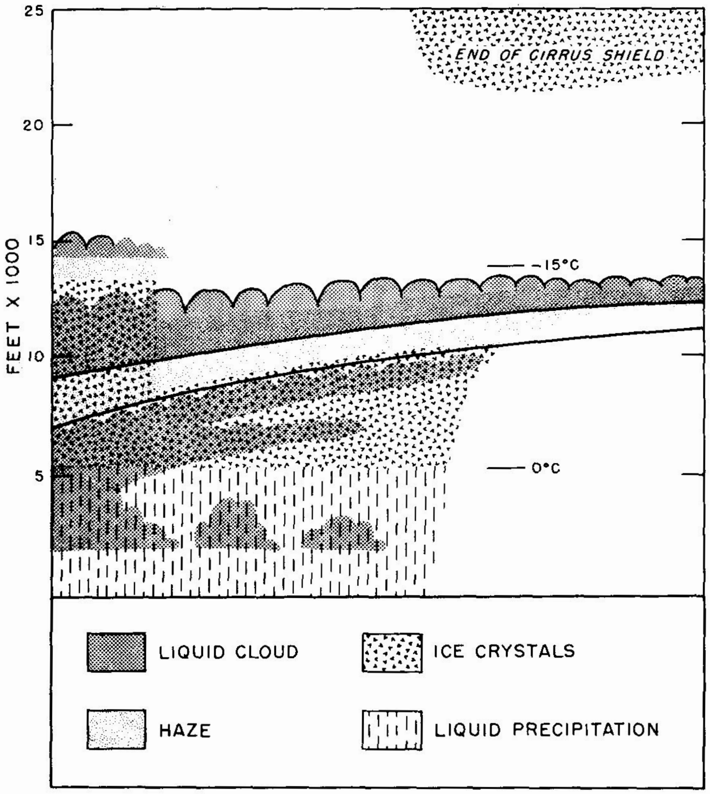

FIGURE 1.—Idealized cloud, frontal, and precipitation system found on the eastern side of winter storms in western Washington State. The types of cloud and precipitation elements involved are shown in the legend and apply also to figures 3 and 12.

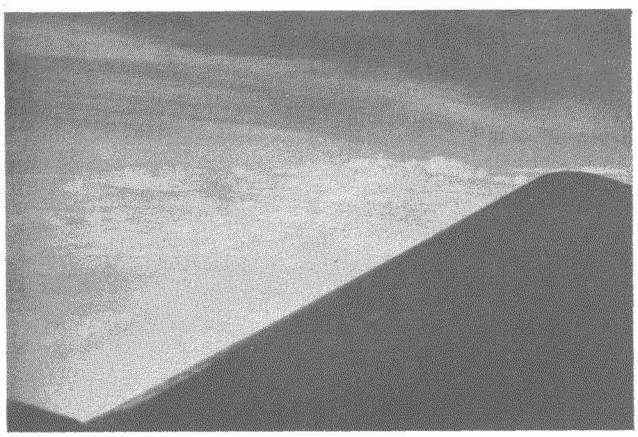

FIGURE 2.—Top of a crystal-generating cloud such as was often observed during ACN Project flights. Altitude 12,000 feet; temperature $-12°$ C. Some of the cumuliform domes are higher than the airplane.

level liquid cloud layers and air of high relative humidity. The top of the upper layer was usually at 12,000 feet or higher and the temperature ranged from $-12°$ C. downward. The appearance of the top varied from that of stratocumulus to cumulus, but the cloud was continuous horizontally and contained indentations in the top sometimes as deep as 2,000 feet. Often there were no clouds above this layer. This sub-cooled liquid cloud provided a generating source of ice crystals with the result that descent beneath it often brought the airplane into an ice crystal environment. Just below this cloud deck, and in the upper portion of the precipitating ice crystal field, the crystals had the appearance of a haze, and were obviously small. At slightly lower elevations however, the crystals became visible as light colored streaks against the dark background of the wings and tail of the plane. At yet lower elevations, there were found one or more layers of low-density liquid cloud, into which the crystals fell and in which they appeared to grow rapidly. In the more intense storms, the water cloud could be found extending several thousand feet above, as well as some distance below, the melting level. It often appeared to develop upward, into the ice crystal field, until depletion by the falling crystals equaled the liquid being condensed. In and below the melting level, some of the precipitation elements grew into rain-sized drops [1], which further increased in size during passage through other liquid layers nearer the surface.

Figure 1 illustrates, in an idealized manner, the cloud and precipitation system in a rather stable configuration. Meteorological activity increases from right to left and the arrangement at the left is characteristic of the region just to the east of the cold front or occlusion. Figure 2 is a photograph of the top of a crystal-generating cloud such as would be found in the situation of figure 1. The altitude of the aircraft was 12,000 feet and the temperature was about $-12°$ C.; surface precipitation downwind from the aircraft location was 0.01 to 0.02 inch per hour in the second hour following the observation. Presumably this was about the time when the observed cloud particles might have been contributing to surface precipitation.

Instability within certain layers caused a more unstable cloud and precipitating system as is shown in figure 3. In this instance the generating clouds are discrete elements but due to wind shear and particle size range, effective blanketing of the lower liquid clouds with ice crystals is accomplished. Figure 4 is a photograph of a smaller type of generating cloud sometimes found on the ACN flights. The tops in this case are estimated to be at 13,000 feet and at a temperature of $-15°$ C.; precipitation at the surface downwind from the location of the observation and in the second hour following amounted to 0.01 to 0.02 inch per hour. Much larger generating clouds were encountered but were difficult to detect and photograph from the aircraft because of their size. They were detected, however, by the vertically-pointing TPQ–6 cloud-detector radar which was situated near the flight area at Hoquiam, Wash. The radar recorded a time section of these generating clouds and their resulting precipitation; a one-hour portion of an operational record is reproduced in figure 5 showing some high-level generating cloud areas with precipitation falling from them. In the illustration each horizontal line represents 5,000 feet in elevation, and the top of the highest echo is near 22,000 feet at an estimated temperature of $-35°$ C.

Of the complex precipitation processes in these cloud systems, crystal generation (nucleation) and natural seeding are the most easily detected. Growth of the falling ice crystals, presumably by the diffusion process,

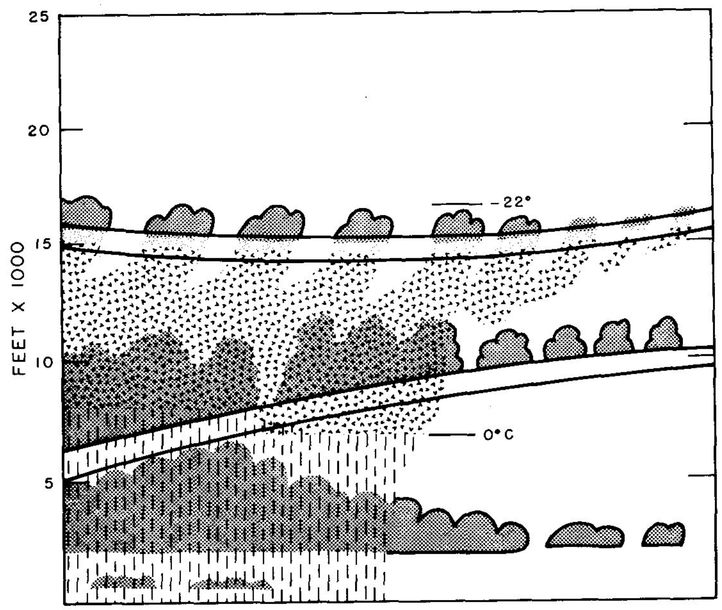

FIGURE 3.—Idealized cloud, frontal, and precipitation system where air layers are unstable. Wind shear and wide range of ice crystal sizes provide blanket seeding of the lower liquid clouds.

FIGURE 4.—Small generating clouds sometimes found above the general cloud deck. Altitude 13,000 feet; temperature −15° C. Streamers of ice crystals can be seen falling from them.

both above the liquid lower deck and within it was observed, and evidence of both coalescence of cloud droplets and aggregation of separate ice crystals was obtained.

3. DIFFUSION

The growth of ice crystals by diffusion is, of course, the process whereby the embryo ice crystal gains mass by incorporating water-vapor molecules into its crystalline structure. For this process to proceed it is generally assumed that water vapor supersaturation with respect to ice must exist in the growth environment. The growth of ice crystals by diffusion was observed beneath the cold, generating clouds during many of the ACN flights, the initial haze just below the cloud base developing into easily visible particles, as mentioned above. Growth within a layer composed of crystals and liquid particles was rapid, and beneath such a layer crystals were large and the crystal field was quite dense.

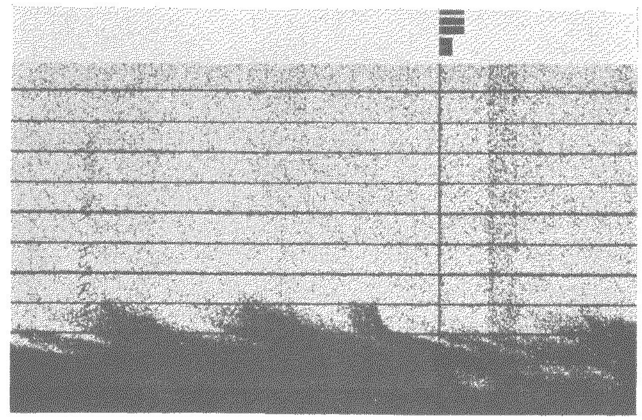

FIGURE 5.—One-hour sample record of vertically-pointing cloud-detector radar. Each horizontal line represents 5,000 feet elevation. Top of the highest echo is about 22,000 feet; temperature there about −35° C.

It is not, of course, to be assumed that diffusion alone caused growth of the ice crystals within the liquid-particle cloud; undoubtedly accretion took place but certainly the higher supersaturation over ice prevailing within the sub-cooled cloud would allow the component of growth by diffusion to proceed at a high rate.

4. COALESCENCE

Coalescence, the process by which one liquid droplet captures another, undoubtedly occurs in the cloud systems of western Washington and accounts for some of the precipitation falling there. Although coalescence cannot be observed from an aircraft flying through a cloud, cloud conditions favorable for its occurrence were often found. Figure 6, for example, shows a photomicrograph of impressions caused by the impact of cloud droplets on the magnesium-oxide coating of a sampling slide [2]. With the large droplets ranging from 100 to 200 microns in diameter and the smaller ones from 20 to 40 microns, terminal velocity ratios as high as 75 to 1 provided excellent coalescence conditions [3]. The sample was taken at 10,000 feet, −4° C., and in light icing conditions. Rainfall rates of 0.10 to 0.20 inch per hour were recorded downwind from the sample location in the second hour following its capture. Twenty minutes earlier the aircraft had descended from 13,000 feet to avoid icing, so it is probable that at the time the sample was collected, coalescence was taking place in more than 3,000 feet of liquid cloud. Conditions favoring coalescence, such as these, were encountered frequently during the flight operations.

On several flights drizzle-sized sub-cooled droplets were encountered by the airplane at relatively cold temperatures. One particularly interesting flight involved the attempt of the plane to top a very severe icing field. At the peak of the climb, at an elevation of 13,500 feet and a temperature of −10° C., a cloud sample was taken. Droplets captured ranged from 300 microns in diameter to about 10 microns, allowing fall velocity ratios of over 100 to 1. The droplet size distribution of

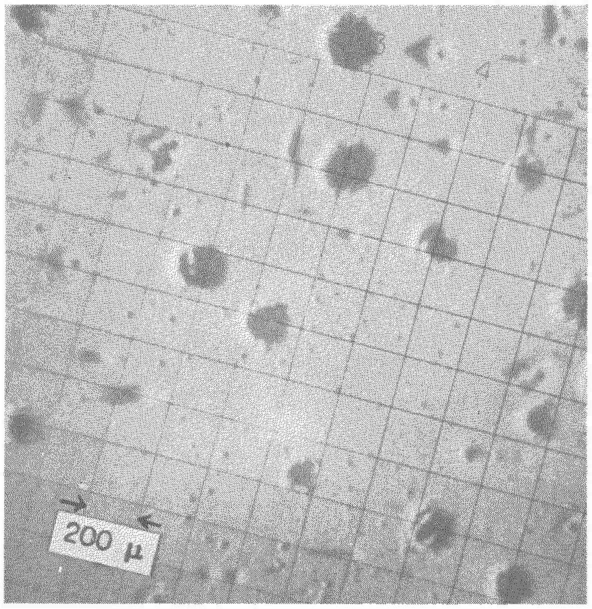

FIGURE 6.—Photomicrograph of impressions caused by impingement of cloud droplets on the magnesium-oxide coating of a cloud-sampling slide. The sample was taken at 10,000 feet and −4° C. in light icing conditions.

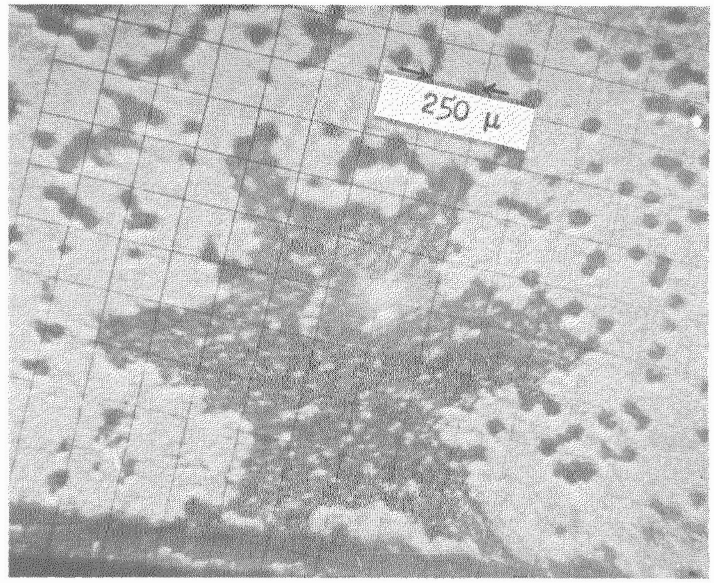

FIGURE 8.—Photomicrograph of imprint of 2000 μ diameter stellar crystal and numerous cloud droplets captured simultaneously on magnesium-oxide coated slide. Sampling conditions: altitude 10,000 feet and temperature −11° C.

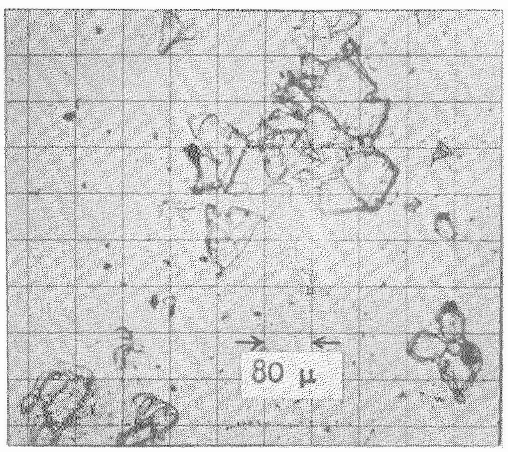

FIGURE 7.—Photomicrograph of formvar replica of aggregate of ice crystals. This sample was captured at 10,000 feet and −8° C., in a homogeneous-appearing and extensive ice crystal field.

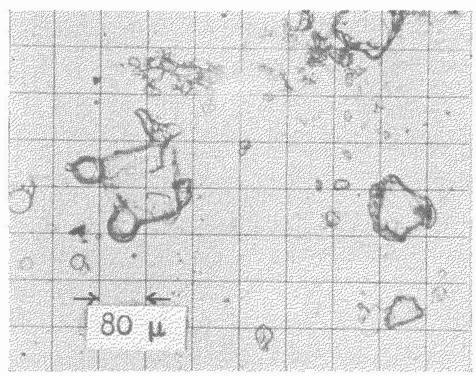

FIGURE 9.—Photomicrograph of formvar replica of atmospheric ice crystals and cloud droplets captured simultaneously. Note two droplets attached to a crystal. These were taken at 10,000 feet at −8° C. in a low-density ice crystal field in which liquid-cloud cells were imbedded.

the sample was bimodal having peaks at around 200 and 15 microns diameter. At the peak altitude the meteorologist reported that although the light intensity was high, he could not see through the cloud layer to blue sky and the sun was not visible; thus a considerable depth of cloud existed above the observation point. No ice crystals were seen in the vicinity of the airplane for some minutes before and after the time of this observation. It seems highly probable that coalescence was a contributing mechanism for the production of such large droplets. Such observations of large sub-cooled droplets are not too rare. Perkins and Kline [4] in 1951 submitted evidence of coalescence of liquid droplets in sub-cooled stratus clouds in the Great Lakes area. Under proper conditions sub-cooled liquid drizzle can even reach the ground as is shown by Kaplan's [5] report of freezing drizzle and rain over a wide area south of the Great Lakes from clouds whose temperatures were below freezing throughout. Coalescence very likely was the mechanism involved in the production of this sub-cooled liquid precipitation.

5. CRYSTAL AGGREGATION

The collision and aggregation of pre-existing ice crystals is also an important mechanism in these cloud systems. During the flights, many ice crystal samples were taken and very often aggregates of crystals were captured. One such aggregate is shown in figure 7, a photomicrograph of the crystal replica. Capture was at an altitude of 10,000 feet and a temperature of −8° C. in a homogeneous-appearing and extensive ice crystal field. In an area estimated to catch precipitation elements from the vicinity of this sample, that is, downwind from the sample location and more than an hour later, rainfall amounts of 0.07 to 0.12 inch per hour were recorded. Jensen [6] has shown that the force necessary to cause cohesion between ice particles is very small, but once adhered several times that force is necessary to separate them if the temperature is not colder than about −12° C. The dense ice crystal field from which the sample was collected afforded excellent opportunity for collisions and the temperature, according to Jensen, was appropriate for a high degree of cohesion. Since the cloud conditions on this flight were typical of those on many flights, it seems logical to conclude that aggregation was a factor in much of the precipitation in the western Washington area.

It is possible that the cluster of crystals in the replica of figure 7 was not adhered before capture, but the conditions for aggregation were quite favorable (a rather dense crystal field and great interaction depth), and the cluster was in an area on the sampling slide containing a rather sparse covering, generally, of single crystals. For these reasons it is believed that the figure shows a natural cluster of ice crystals.

6. ACCRETION

The opportunity for accretion, that is, the capture of liquid droplets by falling ice crystals, was quite frequently observed. The airplane encountered liquid particles within ice crystal fields, often where the crystal field was most dense and the crystals largest. Two examples of conditions favoring accretion are shown in photomicrographs of cloud sample slides in figures 8 and 9. Figure 8 shows the imprint made on a magnesium-oxide slide by a 2000-micron diameter stellar crystal that was captured in a field of liquid droplets whose diameters ranged from 20 to 60 microns. These sizes provided fall velocity ratios between the crystals and droplets of as high as 150 to 1 [7, 8]. Capture was at an altitude of 10,000 feet and at a temperature of −11° C. This appeared to be a case of liquid cloud either forming at the flight level or building up from below. Moisture influx must have been at a high rate to allow condensation in the presence of a crystal field near the temperature of the maximum vapor pressure differential. Figure 9 is a photomicrograph of ice crystals and droplets captured together, and on one platelet fragment can be seen two small droplets. Capture was at 10,000 feet and −8° C. In this case the plane, while flying in a low-density ice crystal field, appeared to be encountering cells of liquid cloud some distance below their tops. At times, relatively small crystal-generating clouds could be observed several thousand feet above the airplane.

These illustrations do not, of course, provide conclusive evidence that accretion occurred in these cases, but it seems highly probable that the faster-falling stellar crystal may have been capturing liquid droplets and that the smaller platelet captured the two smaller droplets before their impact on the formvar-coated slide [9]. The

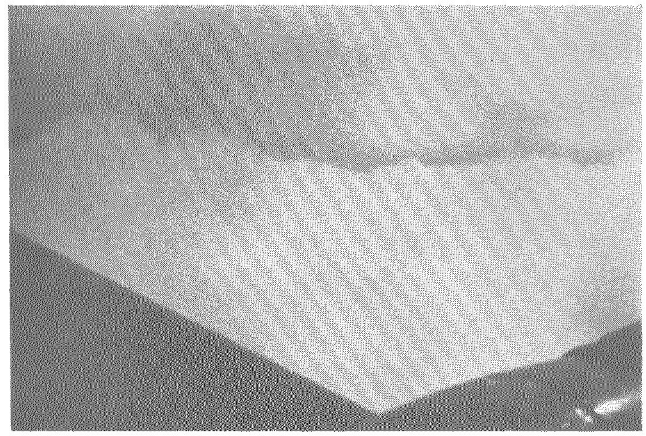

FIGURE 10.—Liquid-cloud-deck top being seeded naturally by higher-level ice crystal cloud. Aircraft altitude 15,000 feet; temperature −18° C. Note the soft, fuzzy appearance of the seeded cloud.

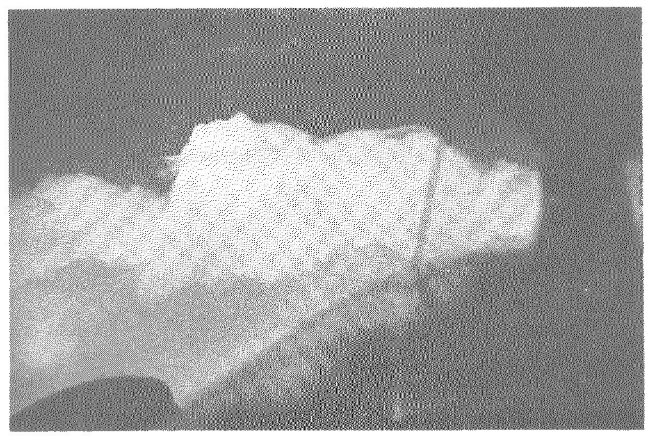

FIGURE 11.—Same cloud deck as in figure 10 but about 15 miles farther west beyond the influence of the upper seeding deck. Altitude and temperature were the same. Note the hard, bright cloud outlines and increased height of the deck.

fact that crystals and droplets, whose fall rates differed, were captured simultaneously certainly indicates that the opportunity for accretion was present.

7. NATURAL SEEDING

On one occasion it was possible to witness the direct effect of natural seeding on a liquid deck. The aircraft was cruising between two vaguely defined layers taking occasional light icing from the undulating top of the lower layer and encountering very small ice crystals falling from the upper deck. Eventually the end of the upper deck was reached but the lower deck extended on outward, and consequently one could observe the appearance of the lower deck both with and without the seeding crystals from the upper cloud. In the portion of the lower deck being seeded, the top was hazy and indefinite, and had a somewhat fuzzy appearance. Figure 10 is a photograph of the upper seeding deck and the lower seeded liquid deck taken from 15,000 feet, and at −18° C. Beyond the influence of the upper deck, in the unseeded portion of the cloud, the average level of the layer was somewhat higher and cumuliform domes were well defined and bright. Figure 11 shows the lower deck beyond the extent of the

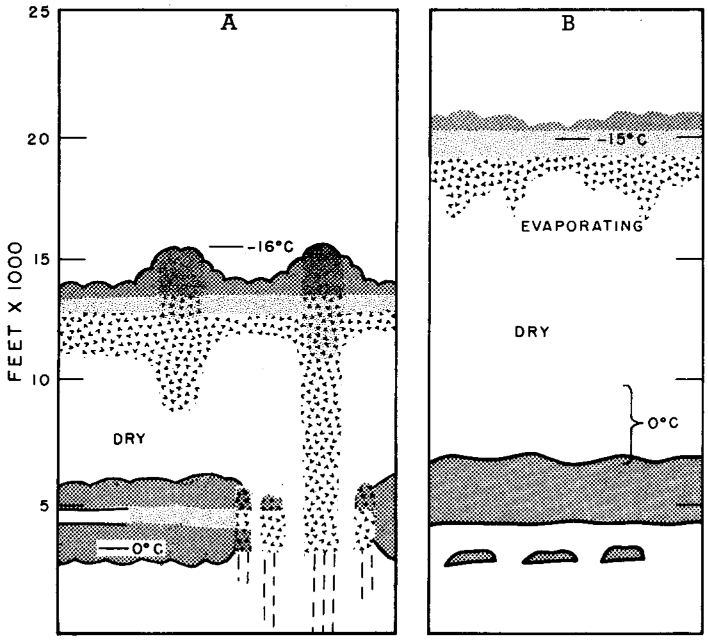

FIGURE 12.—(A) Idealized cloud and precipitation system sometimes found during mild meteorological activity. Seeding showers cut holes in the lower sub-cooled deck. (B) Idealized cloud system found during very light meteorological activity. Seeding particles evaporate before reaching the lower deck, hence there is no production of precipitation from it.

upper ice-crystal-producing deck, taken about five minutes later than figure 10 and at the same altitude. Natural seeding in this instance apparently depressed the top of the lower cloud deck and decreased the cloud density.

On another occasion natural seeding from an upper deck was in the form of scattered ice crystal showers, rather than a continuous ice crystal field. Whenever the showers reached the lower deck, they produced holes which often penetrated completely through the lower deck. Around the edges of the holes one could observe small snow showers continuing to fall, indicative of either the result of spreading of the seeding effect, or illustrating the fact that the seeding was less intense in the outer portion of the snow showers and took longer to develop. Figure 12A shows schematically the cloud deck and precipitation element arrangement just described; this occurred during mild meteorological activity.

8. NON-PRODUCTIVE CLOUD SYSTEMS

On some flights no interaction was apparent between upper and lower cloud layers. The cloud system arrangement usually observed is shown schematically in figure 12B. The dryness of the intervening air layer combined with the weak output of the generating layer prevented the delivery of seeding crystals to the low-level liquid deck. This condition was observed during periods of weak meteorological activity and was characterized by stable thermal stratification of the atmosphere.

9. CONCLUDING REMARKS

The cloud systems surveyed in western Washington exhibited an almost endless variety of structure, and no attempt has been made to present an all-inclusive picture of precipitation mechanisms. The ones described, however, were often observed and possibly are typical of those which occur most frequently, and are probably responsible for a large fraction of the precipitation falling in that area during the winter months. While these results are of a preliminary nature and the conclusions are to a degree inferential, the inflight observations of cloud systems and precipitation processes agree to a great extent with those ou nd in the eastern United States [10].

ACKNOWLEDGMENTS

The writer wishes to thank Messrs. Ferguson Hall and D. B. Kline for numerous helpful suggestions.

REFERENCES

1. Irving Langmuir, "The Production of Rain by a Chain Reaction in Cumulus Clouds at Temperature Above Freezing," *Journal of Meteorology*, vol. 5, No. 5, Oct. 1948, pp. 175–192.
2. K. R. May, "The Measurement of Airborne Droplets by the Magnesium Oxide Method," *Journal of Scientific Instruments*, vol. XXVII, No. 5, May 1950, pp. 128–130.
3. Ross Gunn and Gilbert D. Kinser, "The Terminal Velocity of Fall for Water Droplets in Stagnant Air," *Journal of Meteorology*, vol. 6, No. 4, Aug. 1949, pp. 243–248.
4. P. J. Perkins and D. B. Kline, "Analysis of Meteorological Data Obtained During Flight in a Supercooled Stratiform Cloud of High Liquid Water Content," NACA, *Research Memorandum*, E51D18, July 11, 1951.
5. H. G. Kaplan, "An Analysis of the Freezing Precipitation Situation of December 10–11, 1954, "*Bulletin of the American Meteorological Society*, vol. 37, No. 3, Mar. 1956, pp. 121–124.
6. Delos Clark Jensen, "On the Cohesion of Ice," Thesis, Pennsylvania State University, College of Mineral Industries, 1956.
7. Ukitiro Nakaya and Tôiti Terada, Jr., "Simultaneous Observations of the Mass, Falling Velocity, and Form of Individual Snow Crystals," *Journal of Faculty of Sciences*, Hokkaido Imperial University, II, 1, No. 7, 1935.
8. Choji Magono, "On the Fall Velocity of Snowflakes," *Journal of Meteorology*, vol. 8, No. 3, June 1951, pp. 199–200.
9. I. C. Brown, H. P. Palmer, and T. W. Wormell, "Reviews of Modern Meteorology No. 13, The Physics of Rain Clouds," *Quarterly Journal of the Royal Meteorological Society*, vol. 80, No. 345, July 1954, pp. 291–327.
10. Robert M. Cunningham, "Some Observations of Natural Precipitation Processes," *Bulletin of the American Meteorological Society*, vol. 32, No. 9, Nov. 1951, pp. 334–343.